# A Practical Pedagogy of Wimshurst Machine

Nowadays, most students are familiar with the Wimshurst Machine which is a conventional apparatus able to produce and store bipolar static electricity at moderately high potential (50-70kV). The mechanism, however, maybe not so clear for most students. Numerous learners would attribute efficient electrification to friction. In fact, it is because of induction that Wimshurst Machine could produce an astonishing number of charges in such an instant. In this paper, we propose a practical pedagogy to help students grasp the mechanism of Wimshurst Machine, which is simple, efficient and useful. (figure 1)

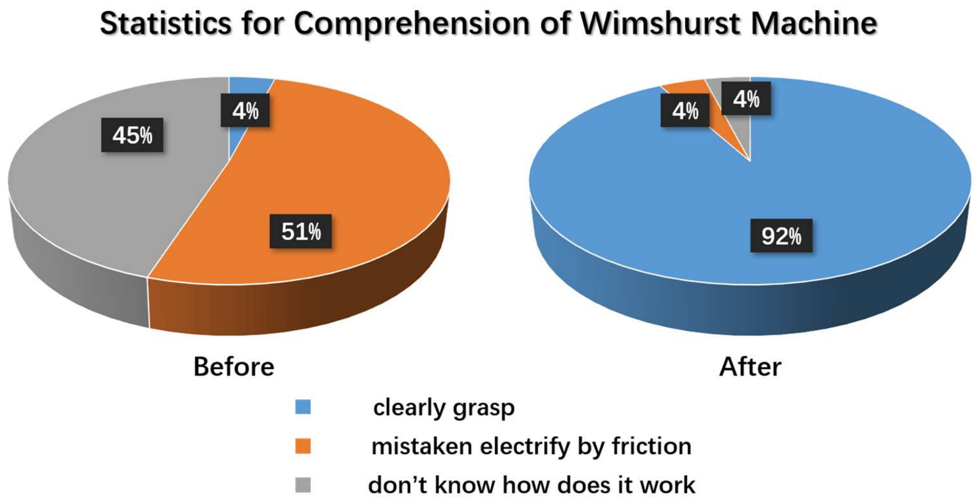


figure 1 We hold a survey in a particular course called *Exploration Common Physical Phenomena*. The main participators are freshmen and sophomore. Among the whole campus, approximate 42 students belonging to kinds of majors attend this course. Before the pedagogy, most students enable to use Wimshurst Machine, but few students have a profound knowledge of mechanism; However, after the pedagogy, as the pie chart shows, most students could understand that rightly.

# 1 INTRODUCTION

The research of the electrostatic machine can be traced back to ancient Greece.[1] With more and more theoretical basis being gradually accumulated, the first Wimshurst Machine was invented by James Wimshurst in 1883, causing excellent results.[2] And the early Wimshurst Machines were frequently used to power X-ray tubes.[3] More than 100 years later, they are no longer responsible for X-ray tubes, while Wimshurst Machine became an excellent platform for students to instruct physical experiments. (For example, in the field of Nano Materials, researchers take Wimshurst Machine for a substantial instrument.[4]) However, few published papers focus on the electrification mechanism, For example, an excellent pedagogy has been demonstrated in Ref.5, which vividly illuminates some basic concepts of electricity and their relationships using Wimshurst Machine, but the author just uses one sentence to explain the electrification mechanism: "Rotating the wheel allows the materials to rub, separating charges." Moreover, this sentence may result in some readers' misunderstanding: they might mistakenly think that Wimshurst Machine's efficient electrification is because of friction rather than induction. In fact, a few people can figure out the mechanism of Wimshurst Machine's electrification.

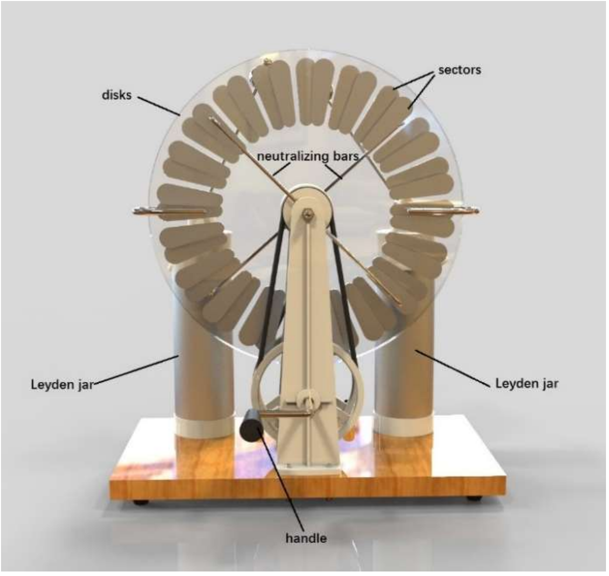


figure 2 The main components of a Wimshurst Machine

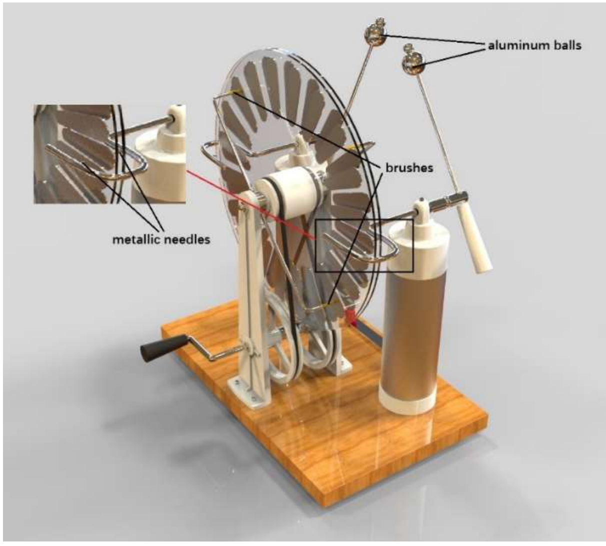


figure 3 The main components of a Wimshurst Machine: Mainly consisting of two disks, two neutralizing bars, two Leyden jars, two aluminum balls, four brushes, a handle and several sectors, a Wimshurst machine can generate visible sparkle between aluminum balls when the handle is rotated toward a specific direction.[6]

# 2 ELECTRIFICATION BY FRICTION

Many students think that friction is vital for Wimshurst Machine to produce high voltage since sectors and brushes rub each other all the time when the machine is working. The discharge phenomenon is related to electron gain or loss by rubbing two kinds of metal materials with different reactivity series (figure 4). Usually, some students are misapprehensive with Wimshurst Machine, because initially in the $19^{th}$ century, inventors even hadn't rigorous design principles of Wimshurst Machine.[7]

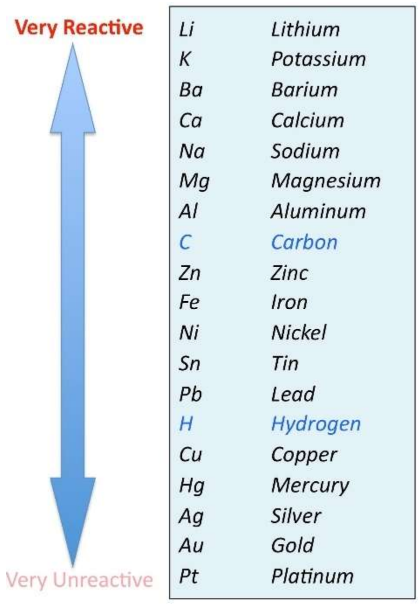


figure 4 Common Metal Reactivity Series. Brushes are made of copper, while sectors are made of aluminum. These two metals are located differently in metal reactivity series.

At this moment, we shouldn't point out mistakes of this explanation immediately, but guide students to figure out errors and make out the answer on themselves. This pedagogy would help students have a good command of physical principles. On the other hand, how do we manage our guidance? We try to lead students to discuss three questions or operate three experiments.

## 2.1 Anti-clockwise Rotating Experiment

It is an actual phenomenon that charge and discharge appearance occurs when we rotate disks toward a particular direction. From the perspective of figure 2, the discharge phenomenon occurs as we turn the handle clockwise. Meanwhile, there's no discharge phenomenon with disks rotated towards the anti-clockwise direction.

Thus, in this experiment, we would ask students how do we explain the phenomenon via electrification by friction? Maybe smart students get the essence before we proclaim the answer.

There is no electric discharge phenomenon when the handle is rotated towards an anti-clockwise direction, which precisely demonstrates that electrification by friction is unfair since the theory of friction is irrelevant to the direction of rotating disks. No matter which direction disks rotate towards, brass brushes always rub with aluminum sectors. Yet according to the experimental phenomenon, it is relevant to the direction of rotating disks whether discharge appearance occurs or not.

Thus, now that friction is not the reason for producing discharge phenomena, what is the reason for producing discharge?

## 2.2 Same-Sectors Experiments

In this experiment, the material of brushes is translated into aluminum from copper. The discharge phenomenon is still observed when disks are rotated clockwise. According to the hypothesis of electrification by friction, there is no process of electron gain or loss when the brushes and sectors with the same metal materials rub each other.

Thus, it's time for students to think whether the hypothesis of electrification by friction is fair to explain this phenomenon reasonably.

## 2.3 The angle between the Bars Experiment

To explore the mechanism of the Wimshurst machine further, Angle between Neutralizing Bars Experiment is necessary and worthwhile. We change the perspective of two bars and then rotate the handle clockwise. The discharge phenomenon can be observed, but the efficiency declines, which is visible for our naked eyes that sparking reduces between aluminum balls. After changing the angle between two bars, the brushes and the sectors still rub each other at the same rate, so the efficiency would not go down if the hypothesis of electrification by friction is right.

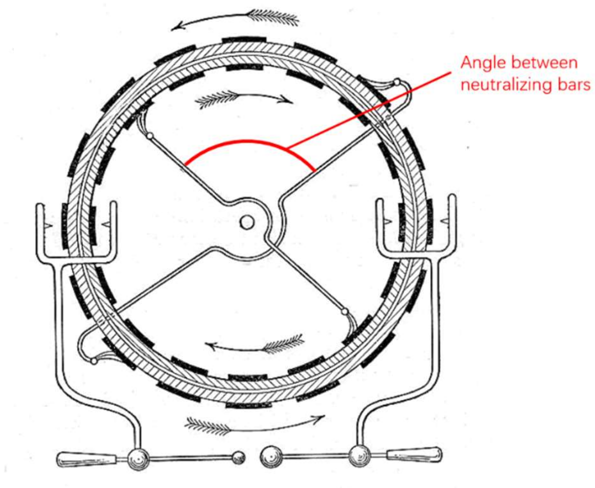


figure 5 the sketch maps of Wimshurst Machine from the perspective of figure 2

Therefore, students should reflect on the phenomenon. How do they explain that with electrification by friction? If they don't. Whether the theory and hypothesis of electrification by friction is untenable or not?

# 3 ELECTRIFICATION BY INDUCTION

It is necessary that students are given the right answer after abundant pondering, especially for the above three experiments. Brushes made of copper and sectors made of aluminum are occupied in different metal reactivity series. However, the reason why the discharge phenomenon is not resulted from electrification by friction is that air surrounding us is so stable that metal couldn't show their reactivity. We often mention the metal reactivity series. It is in the sulfate liquid that copper and aluminum could show their metal reactivity. For example, aluminum could replace copper from copper sulfate liquid.

Hence, it is because of electrification by induction that the Wimshurst Machine enables to produce such high voltage and discharge phenomenon occurs. The electric circle could be applied for explaining the electrification by induction.[8] Similarly, mathematics or matrix could be used for that.[ 9,10] These two methods are unavoidably complex, especially for rudimentary physical learners, and for the particular course which art primary students would attend.

To clarify this series of discharge phenomena more succinctly, we merely do some qualitative analysis and simple calculation of geometric progression.[11]

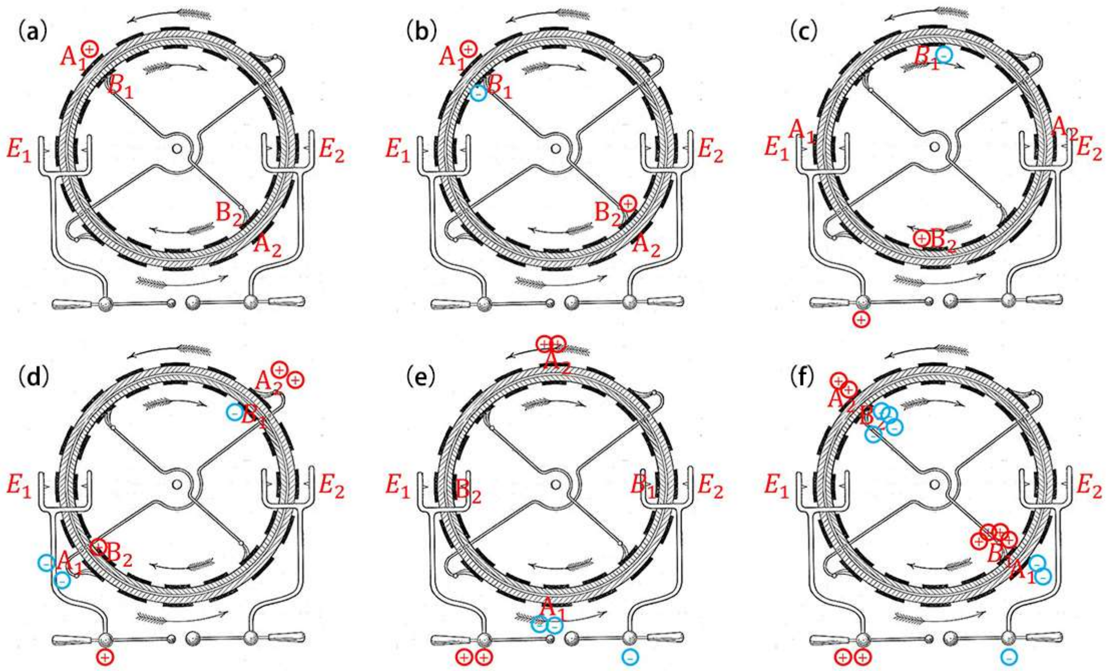


figure 6 The process of charge transport when the handle rotated clockwise. In order to simplify, Leyden Jar hasn't been drawn on the figure.

$E_1$ and $E_2$ are the location of metallic needles; $A_1$, $A_2$, $B_1$, $B_2$ are sectors of a certain site. Suppose that one positive ion from atmosphere sticks to the $A_1$.figure 6(a)(The perturbation of charge is full of our surrounding atmosphere; And the positive ion or negative ion often escapes from disks or sectors in a humid atmosphere.[12]) It will induct a negative charge at the $B_1$.

When the disks are rotated, as $A_1$ moves to the left and $B_1$ moves to the right, the positive ion at the $A_1$ turns to the $E_1$ which is near to the needles. The charges at the sectors give rise to the point discharge when the vectors are very close to the needles. So this ion is transported from sector to the needle and then travels down to the conductor to the Leyden Jar. The negative charge at the $A_2$ is transported to Leyden Jar in the same way.(figure 6(c)) As a result, the imbalance of charge leads to the generating of two negative charges at the two appropriate locations.( figure 6 The process of charge transport when the handle rotated clockwise. In order to simplify, Leyden Jar hasn't been drawn on the figure. With the trend like this, the number of charges by induction next time will increase exponentially as $2^2$, $2^4$, $2^8$···( figure 6(e)(f)) The amount of charge at two Leyden Jars will mirror a kind of explosive growth. Consequently, the total charge number at one Leyden jar can be analytically described as follows:

$$1+2^0+2^1+2^2+\cdots+2^{4n-2}=1+\frac{2^0-2^{4n-2}\cdot 2}{1-2}=1+(2^{4n-2}\cdot 2-1)=2^{4n-1} \tag{1}$$

The mechanism referred above is based on the precondition that only one charge from atmosphere sticks to one of the sectors of the Wimshurst machine. It can be easily extended to the general case in which more than one charge sticks to the sectors by using the adding principle. The number of original charges at each foil can be described as $G_1$, $G_2$······$G_m$, as shown in Figure 7.

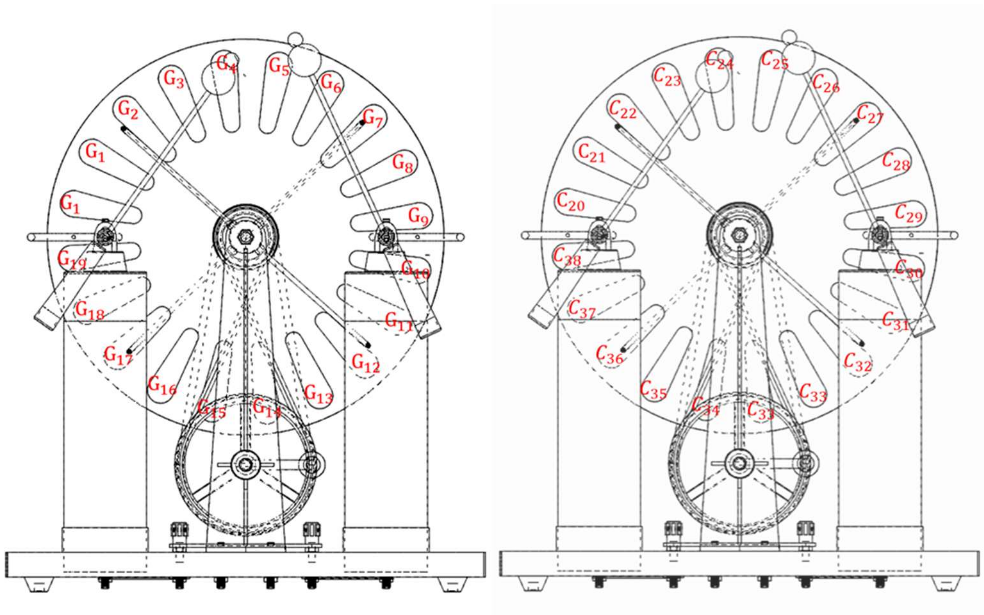


figure 7 The left one is front disk, and the right one is back disk from the perspective of figure 2. They show the original number of charges in every sector.

By the above analysis, after rotating N circles, the Leyden Jar would accumulate about $(\sum_{i=1}^{i=38} C_i)2^{38N-1}$ units charges.

Up to now, return to the three experiments: Anti-clockwise Rotating Experiment; Same-Sectors Experiments; The angle between the Bars Experiment. We haven't explained the first one and the third one. We advocate that the explanation of experiments with electrification by induction shall be arranged as a group project or homework for students because the best teaching method is not to infuse knowledge to students but to guide students to explore knowledge by themselves.

At last, after students finishing the above homework and understanding the Wimshurst Machine's working principle to some extent, we demonstrate another machine called "Maschinchen" and developed by Einstein.[13] Both two kinds of the device have similar electrification mechanism: charging by induction, the accumulation of the number of charges presents exponential growth, and the efficiency of electrification is exceptionally high. That is why an electrical induction machine is superior to an electrical friction machine. The example of Maschinchen, working as supplementary material, can help students have a deeper understanding of the theory of induction electrification.

# 4 SUMMARY

Wimshurst Machine is the best known because of its widespread use in educational institutions all over the world. However, the presence of two counter-rotating disks makes it challenging to explain it to students.[14] Namely, most students don't have a distinct knowledge of the mechanism that Wimshurst Machine produce charges. We propose a pedagogy for teaching the mechanism, in order to correct students' misapprehension and build up the right conception of Wimshurst Machine.

# 5 REFERENCE


[1] http://www.hp-gramatke.net/history/english/page4000.htm.

[2] J. Gray, Electrical Influence Machines, Whittaker1890, pp. 149-170.

[3] A.C.M.d. Queiroz, http://www.coe.ufrj.br/~acmq/wimshurst.html, 1996.

[4] C.C. Qin, X.P. Duan, L. Wang, L.H. Zhang, M. Yu, R.H. Dong, X. Yan, H.W. He, Y.Z. Long, Nanoscale, 7 (2015) 16611-16615.

[5]W.Chang. Am. J. Phys., Vol. 79 (2011)226-238.

[6] M.B. Ege, A. Font, S. Bolat, O. Kalenderli, 2014 ICHVE International Conference on High Voltage Engineering and Application, IEEE2014, pp. 1-5.

[7] B.J. Cosman, Massachusetts Institute of Technology1937.

[8] H.M. Aguilar, Lat. Am. J. Phys. Educ. Vol, 8 (2014) 100.

[9] A.W. Simon, Review of Scientific Instruments, 4 (1933) 67-74.

[10] A.W. Simon, Physical Review, 28 (1926) 545-553.

[11] J.H. Poynting, J.J. Thomson, A Text-book of Physics: Electricity and Magnetism, Parts I and II, Static Electricity and Magnetism, C. Griffin1914, pp. 18-21.

[12] J. Gray, Electrical Influence Machines, Whittaker1890, pp. 163.

[13] D.Segers, J. Uyttenhove. Am. J. Phys., Vol. 74 (2006)670-676.

[14] A. Aresti, A. Delunas, American Journal of Physics, 51 (1983) 472-473.